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A strategic impact assessment of hydropower plants in alpine and non-alpine areas of Europe

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HIGHLIGHTS

- Environmental impacts of hydropower plants in Europe is investigated by LCA analysis.
- Impacts are estimated by the ReCiPe 2016, Impact 2002+, and Eco-points 97 methods.
- Hydropower plants of alpine regions are found least hazardous to the environment.
- Plants of non-alpine areas are 10 times responsible for climate change than alpines.

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ABSTRACT

Hydropower is the widely used source of clean energy which includes some hazardous emissions that affect human health, ecosystems, and resources. However, in spite of an enormous amount of hydropower generation in Europe, no research has been carried out in evaluating the hazardous emissions from the plants located in alpine and non-alpine areas. Therefore, this paper will analyse the comparative environmental impacts of hydropower plants in alpine and non-alpine areas of Europe by a systematic life-cycle assessment (LCA) approach. The impacts are estimated by the ReCiPe 2016, Impact 2002+, Eco-points 97 methods under a number of effect-assessing indicators such as global warming, ozone formation, eco-toxicity, water consumption, acidification, eutrophication, ionizing radiation, carcinogenic radiation, ozone depletion, and land use. Moreover, the fossil-fuel-based power consumptions and the greenhouse-gas emissions in the life-cycle of hydropower plants in both locations are estimated using the Cumulative Energy Demand (CED) and the Intergovernmental Panel on Climate Change (IPCC) methods, respectively. The outcomes reveal that hydropower plants of alpine regions offer a better environmental profile for the global-warming indicator (2.97×10^{-5} kg CO_2-eq/MJ) than non-alpine plants (3.92×10^{-4} kg CO_2-eq/MJ), but the effects are nearly identical for the other indicators. Overall, the hydropower plants of non-alpine regions are responsible for climate change with a rate 10 times as high as for alpine ones. The findings of this research will play a pivotal role in promoting sustainable production of hydropower, especially the full potentials of the alpine region, and thus leading towards environmentally friendly clean renewable electricity generation.

1. Introduction

Nowadays the global energy demand is rising due to the growing world population and industries. Therefore, the fossil-fuel-based power generation rate has been increased to meet the growing demand [1,2]. These large numbers of conventional power-generating units release dangerous greenhouse-gas (GHG) emissions during power production [3–5]. For that reason, the world climate is being negatively changed [6–9]. People are getting more concerned about the ecosystem, thinking about the future unavoidable threats of the hazardous emissions to the environment, and have agreed to reduce global CO_2 emissions to enhance the level of life comfort. Therefore, to save the environment and to reduce the use of conventional power-generation systems, renewable energy production is getting considerably more popular day by day [10–14]. In the coming few decades, we will observe an unprecedented use of renewable sources for power production. Among renewable energy technologies (RET), hydropower is considered to be the cleanest power-generating source [15,16]. It has often

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been installed in alpine and non-alpine regions of Europe due to the availability of resources [17–19]. However, previous research shows that hydropower plants release hazardous emissions during the construction phase [20,21]. Taking this fact into account it is increasingly important to do research on the quantification of the pollution by hydropower plants located in alpine and non-alpine areas of Europe.

In spite of an enormous amount of hydropower generation all over the world, only a few studies have been carried out to evaluate the dangerous emissions in the processing route of the plant [20–23]. A case-study-based research accomplished by Botelho et al. highlighted a comparison of the environmental impacts of the hydropower plants in Portugal, raising problems such as that fauna and flora are most commonly affected by the impacts [24]. They did not consider the whole life-cycle of the plants. Ribeiro et al. examined the life-cycle inventory (LCI) of hydroelectric power generation in Brazil, but they did not use a global database [25]. The carbon footprints of two large hydro-projects in China was revealed by Zhe Li et al. following life-cycle assessment (LCA) according to the International Organization for Standards (ISO) 14067 [26]. They did not consider metal-based emissions and did not precisely quantify the impacts on human health, ecosystem, resources and climate change. Pang et al. and Li et al. recommended that the use of environmentally friendly materials and optimization of the plant design is required to reduce the impact of a small hydropower plant in China, as it releases the most hazardous gas during the construction phase [27,28]. The rate of greenhouse gas emission and associated uncertainties in the LCA analysis are represented by Hondo et al. for a hydropower plant in Japan [29]. An Indian research group (Varun et al.) has considered three hydropower plants with different capacities and locations and assessed their impacts through life cycle analysis [30]. Hanafi et al. from Indonesia accomplished an LCA of a mini hydropower plant and suggested that carcinogenic and freshwater aquatic eco-toxicity are mostly responsible for the impact occurring during the construction phase [31]. The impacts associated with a community hydropower plant in Thailand are assessed by Pascale et al. [32]. They showed that the considered plant performed environmentally superior to a diesel generator. An investigation run by Geller et al. considering a small hydropower plant in the Brazilian Amazon depicted that the steel used in the turbines and concrete in buildings are crucial for the overall impacts by the plant [33]. A Canadian research team (Siddiqui et al.) has compared the impacts of a hydropower plant with equivalent wind and nuclear plants [34]. According to their research the global warming, acidification, and eutrophication potentials are the key impact indicators of a hydropower plant. The major contributions and relevant research gaps of the previous studies with similar interests are highlighted in Table 1. However, to the authors' knowledge, no research has been done in finding the impacts of alpine and non-alpine region-based hydropower plants and comparing their effects. Therefore, it is essential to quantify the impacts by a systematic approach considering all input and output flows during the whole lifespan and the end-of-life waste-management schemes of the plants.

This research is aimed at estimating the hazardous effects of the plants of alpine and non-alpine areas by LCA, as it is widely accepted as a systematic approach to evaluating the ecological effects of a power production plant throughout its lifespan; from raw-materials extraction through to processing, transport, operation and end-of-life disposal [42–45]. SimaPro software version 8.5 is used in this research work for assessing the impacts by systematic LCA [46]. The impacts are obtained under fourteen impact indicators: carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone-layer depletion, respiratory organics, aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acid, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction. The ReCiPe 2016 and Impact 2002+ methods are utilized in assessing these effects. These effects are categorized under four major indicators: resources, climate change, ecosystem quality, and human health. The Eco-points 97 method is used to investigate metal- and gas-based dangerous emissions. Furthermore, GHGs such as carbon dioxide, methane, nitrous oxide etc. emitted into the air are estimated by The Intergovernmental Panel on Climate Change (IPCC) method. Therefore, the major contributions of this work can be summarized as follows:

- Carries out research into the environmental hazard estimation of existing hydropower plants in Europe.
- Creates a unique life-cycle inventory (LCI) for hydropower plants located in both alpine and non-alpine areas of Europe to assess their environmental hazards in terms of ecosystem, climate change, resources and human health.
- Performs a step-by-step LCA analysis to find the GHG and metal-based emissions of both categories of plants.
- Completes an uncertainty analysis for both categories of hydropower plants.

This research work is unique as it quantifies the environmental effects by several standardized approaches for the first time and considers both the mid-point and end-point impacts of both categories of plants considering the cradle-to-grave LCA boundaries.

In the light of the preceding, the rest of the paper is organized as follows. Section 2 highlights the countries of alpine and non-alpine areas in Europe and their hydropower production scenario. In Section 3 an overview of the life-cycle assessment method is highlighted. Section 4 depicts the results of the environmental profiles, metal- and gas-based emissions, greenhouse-gas releases, life-time inputs and outputs, and energy consumption rates of the plants. Section 5 discusses the impact outcome comparison with previous studies, impact comparison with other types of power plants, and uncertainty analysis of the plants. The limitations of this study are highlighted in Section 6. Finally, concluding remarks on the research outcomes and future recommendations are presented in Section 7.

2. Hydropower plants of alpine and non-alpine areas in Europe

The alpine region covers the countries which are surrounded by the Alps mountains. There are eight European countries which share their border with the Alps: Italy, France, Austria, Switzerland, Liechtenstein, Germany, Slovenia and Monaco. Fig. 1 shows the boundary of the alpine countries in Europe [47]. Among these eight countries, five have significant production of hydropower. Fig. 2 describes the 25 European countries which have hydropower plant. Among these 25 countries, five countries are located in the alpine region while the others are located in the non-alpine region. Fig. 2 also shows the installed capacity of hydropower plant per country with the number of installed plants. The details of the alpine countries with hydropower plants and their production details are described in Table 2. The leading hydropower generating countries in Europe are Germany, Austria, Italy, Spain, Sweden and France [48]. Among these six countries, four are alpine countries with 42% of their total electricity production by hydropower plants. Table 3 shows the leading non-alpine countries with hydropower production. Tables 2 and 3 show the total number of hydropower plants in 2007 and 2011, their installed capacities, and their yearly production. According to the information presented in Table 2 for alpine countries, Germany is the leading country in hydropower plants installed in the alpine region, followed by Austria, Italy, France and Slovenia. Table 3 illustrates the leading non-alpine countries with hydropower production: these are Sweden, the Czech Republic, Spain, and Poland [48].

3. Methodology

The aim of this research work is to analyze the environmental impact of the hydropower plants of alpine and non-alpine areas of Europe. The analysis is made using the LCA approach, a powerful tool for checking the carbon footprints of any product, unit, or system [49–52].

Table 1
Recent studies on life cycle assessment of hydropower plants and the research gaps.

Source Ref.	Topic	Major Contributions	Research Gaps
[25]	Life-cycle inventory for hydroelectric generation: a Brazilian case study.	A life cycle inventory (LCI) for hydropower plant of Brazil has been developed.	The estimation of environmental and social impacts has not been accomplished in this research.
[26]	Carbon footprints of two large hydro-projects in China: Life-cycle assessment according to ISO/TS 14067.	Carbon footprints of the two projects are compared with over 150 worldwide cases.	The impacts of reservoir sediments of the plants have not been assessed.
[35]	A benchmark for life cycle air emissions and life cycle impact assessment of hydrokinetic energy extraction using life cycle assessment.	GHG emissions have been quantified for a hydrokinetic energy extraction system and compared with other power generation types such as coal, gas, nuclear plants etc.	The replacement of toxic fiberglass materials has not been identified, which is needed to be replaced by a possible option for a superior environmental profile of the considered system.
[36]	Ecosystem impacts of alpine water intakes for hydropower: the challenge of sediment management.	The impacts of flow abstraction and the challenges of sediment management upon ecosystems has been revealed through a systematic review. The main characteristics of natural Alpine stream aquatic ecosystems have also been highlighted.	The impact of hydropower plants in the alpine zone has not been considered and explored in this work.
[37]	Impacts of climate change, policy and water-energy-food nexus on hydropower development.	A review of the impacts from policy, climate change and water-energy-food nexus on hydropower development has been explored at global scale.	The social and environmental influences of hydropower generation systems have not been depicted to justify the overall welfare.
[38]	Emissions from tropical hydropower and the IPCC.	This work points out that the emissions from dams need to be considered in inventories of the Intergovernmental Panel on Climate Change (IPCC), which have been overlooked.	They have not considered other LCA approaches like ReCiPe, Impact2002+ etc.
[39]	Life-cycle inventory of energy use and greenhouse gas emissions for two hydropower projects in China.	The environmental performance of two hydropower plants of China has been assessed by an economic input–output based life cycle assessment method.	The metal-based emissions have not been considered and estimated in this work.
[40]	Accounting for GHG net reservoir emissions of hydropower in Ecuador.	The environmental impacts of dam and run-of-river based hydropower plants of Ecuador has been evaluated by the life cycle assessment approach.	The social aspects of the plants have not been assessed.
[41]	Addressing biogenic greenhouse gas emissions from hydropower in LCA.	A statistical analysis of methane and CO_2 emissions from hydropower plants has been carried out to assess the sustainability.	The influences of the plants on human health, ecosystem quality and climate change have not been highlighted.

The LCA has often been applied in calculating environmental effects and checking sustainability [44,53,54], which is generally carried out by following the ISO standards 14040:2006 and 14044:2006 [55–57].

The scope of this research work is the inventories collected from the database for the considered plants. The LCA is done using SimaPro software. The analysis methods are selected as ReCiPe 2016, Impact 2002+, Eco-points, and IPCC. These methods are widely used for life-cycle environmental impact evaluation related to energy production

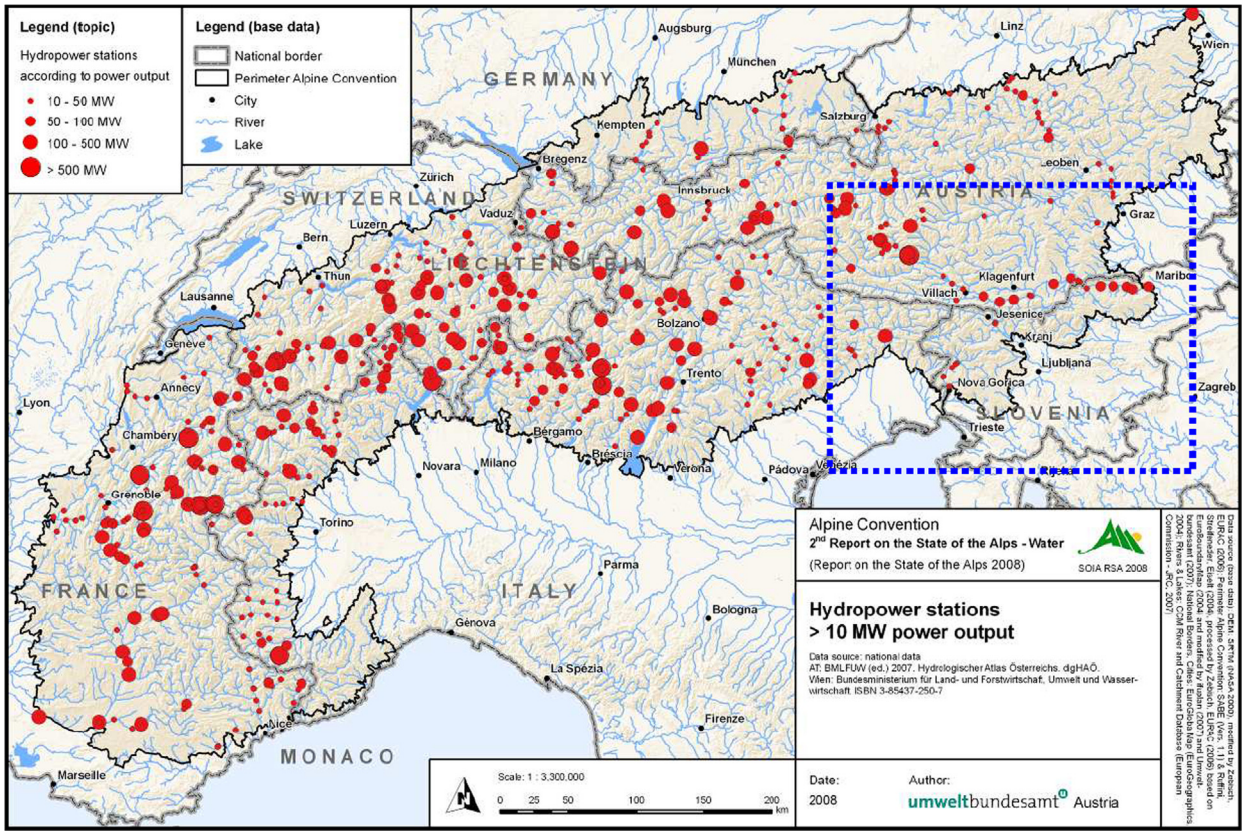

Fig. 1. Map of the alpine boundary in Europe (Source: 2nd Report on the State of the Alps) [47].

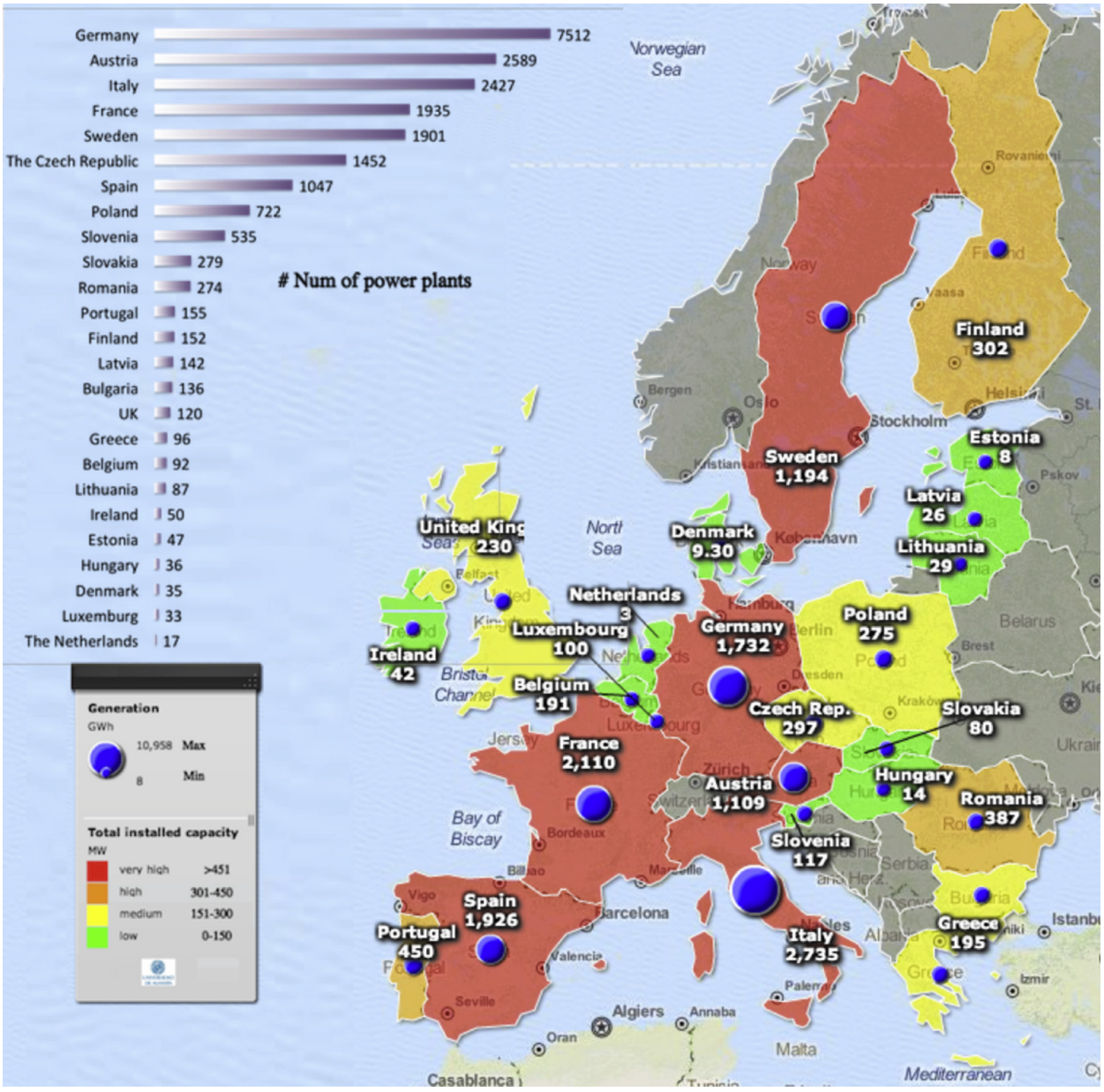

Fig. 2. Hydropower production scenario in alpine and non-alpine areas of Europe [48].

Table 2
The hydropower production details for the alpine areas in Europe.

Country	Plants in 2011	Plants in 2007	Capacity (MW in 2011)	Production (GWh/year)
Germany	7512	7503	1723	8352
Austria	2993	2354	1284	5778
Italy	2601	1835	2896	10958
France	1935	1825	2110	6820
Slovenia	471	456	118	587

Table 3
The hydropower production details for the non-alpine areas in Europe.

Country	Plants in 2011	Plants in 2007	Capacity (MW in 2011)	Production (GWh/year)
Sweden	1867	1813	1283	4350
Czech Republic	1475	1405	297	1159
Spain	1250	553	1926	4719
Poland	739	681	281	1035

technologies [58–60]. In this study, LCA is carried out maintaining four fundamental steps:

1. Goal and scope definition, where the aim is depicted and boundaries are identified.
2. Life-cycle inventory, where the energy, material and emission-based input–output flows are assembled.
3. Life-cycle impact estimation, where effects are estimated for fourteen impact assessing indicators.
4. Impact outcome interpretation, where effects are justified with the goal.

These key steps are shown in Fig. 3 and highlighted in the following subsections to depict the LCA method used in this research.

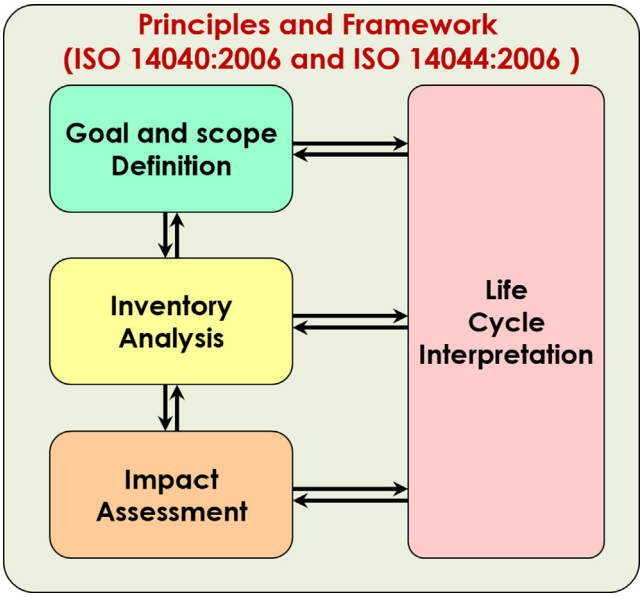

Fig. 3. Stages of the life-cycle assessment method [61].

3.1. Goal and scope definition

In the first step of LCA, the main aim is identified as the comparative evaluation of the environmental threats of the hydropower plants of alpine and non-alpine zones. It helps to recognize the best hydropower generation plants' locations in Europe from an environmental perspective. The LCA is done considering the cradle-to-grave LCA boundary for both locations of the plants. Therefore, the total inputs and outputs of the whole lifespan of the plants are considered in assessing the impacts, which is obtained from the database. Figs. 4 and 5 respectively show the rate of energy and materials flow in various stages of the hydroelectricity generation in alpine and non-alpine areas. The functional unit is considered as one MJ of energy production, which identifies the rate reference flow [62,63]. This one MJ functional unit reveals the electrical energy amount which is available for consumption at the distribution terminal.

3.2. Life-cycle inventory

The second step of LCA is the development of an LCI counting all the input–output materials, energies and emissions. For that purpose, an LCA system boundary is considered in this research as depicted in Fig. 6. The inventory datasets of considered hydropower plants located in alpine and non-alpine regions were originally documented in [64], and were later compiled into Ecoinvent version 2 database. These datasets are now available in the Australian life cycle assessment database (AusLCI). The datasets contain estimated values taking the average of more than 50 reservoir hydropower plants rated from 0.5 to 1200 MW in alpine and non-alpine areas of Europe. The weighted value of hydropower production is utilized to calculate the average material requirements. The raw materials, resources, organic and inorganic chemicals are used to build the elements of hydropower plants. These plant elements along with construction materials (cement, gravel, concrete and steel) are used to build the plants. The life cycle inventory includes all equipment for plant infrastructure construction, operation, and waste emissions. Fig. 6 represents the life-cycle assessment system boundary considered in this LCA process.

The total inputs of a plant are of various types: raw materials, water, nonrenewable energy, organic and inorganic chemicals, transportation and other available resources at the specific plant location. However, the output is 1 MJ of electricity production and waste emissions. Tables 4 and 5 show inputs from nature and the technosphere, and outputs to

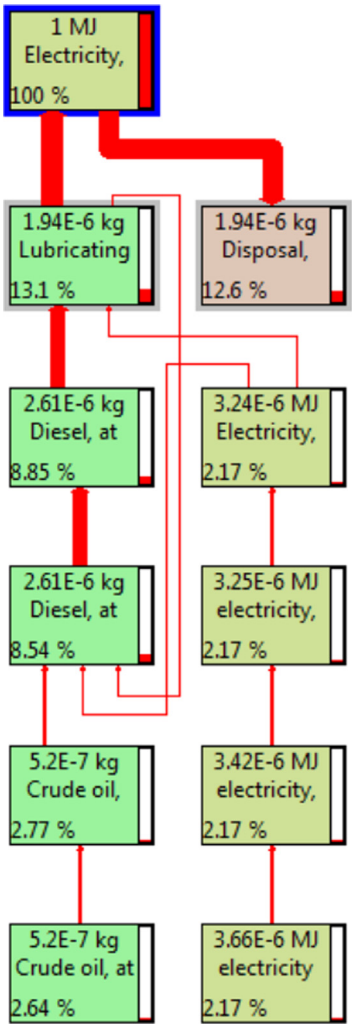
1 MJ Electricity, 100 %
1.94E-6 kg Lubricating 13.1 %
1.94E-6 kg Disposal, 12.6 %
2.61E-6 kg Diesel, at 8.85 %
3.24E-6 MJ Electricity, 2.17 %
2.61E-6 kg Diesel, at 8.54 %
3.25E-6 MJ electricity, 2.17 %
5.2E-7 kg Crude oil, 2.77 %
3.42E-6 MJ electricity, 2.17 %
5.2E-7 kg Crude oil, at 2.64 %
3.66E-6 MJ electricity 2.17 %

Fig. 4. Materials flow sheet for 1 MJ of hydropower generation in an alpine region.

the air and technosphere by the considered plants, collected from the LCI datasets. They show that the input amounts are almost identical for both plants. It also reveals that the amount of mineral oil disposal is identical for both systems, but non-alpine-region based hydropower plants produce more biogenic methane emissions than alpine-area based installations.

3.3. Life-cycle impact estimation

The third step of the LCA is life-cycle impact assessment, done following ISO 14044:2006, where emissions and input parameters are arranged into their respective impact indicators and converted into the same unit for comparative assessment. For calculating impacts, SimaPro software version 8.5 [46,65] and the Ecoinvent database were used for the considered plants due to their global acceptance [66,67]. The ReCiPe2016 method is used to assess the mid-point environmental impacts under categories such as global warming, ozone formation, ecotoxicity, water consumption etc. This method is the updated version of ReCiPe2008 done by Huijbregts et al. last year, which considered 17 mid-point effect assessing indicators in characterizing the overall impacts of a system [68]. It characterizes the environmental effects of a product through transforming life cycle inventories into a number of impact categories in a unique state-of-the-art approach.

The Impact 2002+ method is used to measure the end-point effects under four categories: resources, climate change, ecosystem quality and

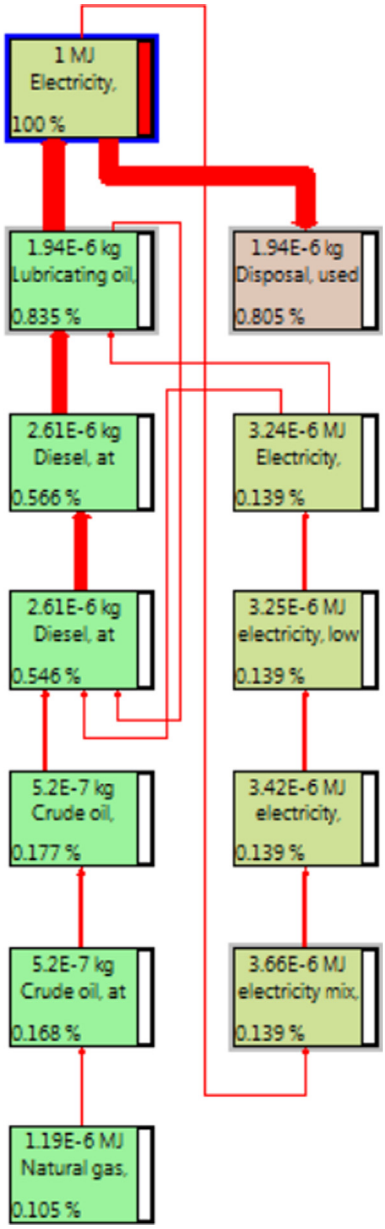

Fig. 5. Materials flow sheet for 1 MJ of hydropower generation in a non-alpine region.

human health [69]. Human damage indicators are estimated considering carcinogenic and non-carcinogenic emissions. Furthermore, impacts relating to human toxicity and eco-toxicity are obtained by average responses instead of assumptions.

The IPCC method is used to evaluate the greenhouse-gas emissions following a 100-year time span. This method considers emissions like carbon dioxide, methane, nitrous oxide etc.[38,70] This approach offers three benefits in assessing the GHG emissions: a) ensures best use of the data source in a comprehensive manner, b) establishes transparency in assessment, and c) provides insights for policymakers on climate solutions [71]. It does not consider carbon monoxide emissions and radiative releases in the stratosphere. Fig. 7 shows an overview of the LCA methods (ReCiPe 2016, Impact 2002+ and IPCC) used in this research.

The fossil-fuel-based energy consumption rates by the plants have been evaluated by the Cumulative Energy Demand (CED) approach. The CED method considers all types of energy usage such as nuclear, biomass, renewable, fossil fuel (oil, coal and gas) at the overall life cycle of the plants and provides a breakdown of energy consumption [72]. It is pivotal to get information of the fossil-fuel consumption by the plant to replace them by renewable energy for a superior environmental profile. Hydropower plant usually consumes a small amount of fossil-fuel during production and maintenance. However, it consumes a significant amount of carbon-based-fuel during the raw material extraction to the manufacturing of the plant elements [73]. Finally, uncertainty analysis has been performed by the Eco-indicator 99 method [74] to check the probability distribution of the considered cases for both plants.

3.4. Impact outcome interpretation

The final step of LCA is the life-cycle impact interpretation, where effect outcomes are analyzed and compared with the main LCA goal of this research. At this stage, we identify the significant factors that account for environmental hazards by each of the plants. Uncertainty analysis has been undertaken to interpret the LCA outcome in a broader perspective.

4. Results

4.1. Comparative environmental profiles of the hydropower plants

The environmental performances of hydropower plants in alpine and non-alpine regions of Europe are measured by the ReCiPe 2016 and Impact 2002+ methods [58]. The ReCiPe 2016 method is used to measure and compare the mid-point effects of the plants considering raw material extraction to electricity production, while the Impact 2002+ method is used to estimate and compare the end-point impacts of the plants considering raw material extraction to end-of-life waste disposal.

4.1.1. Mid-point impact assessment outcome

Fig. 8 shows the comparative global-warming-based effects of the considered plants obtained by the ReCiPe 2016 approach. Global-warming-related emissions mostly affect human health. The hydropower plants of non-alpine zones (weighted value of 4.16×10^{-9} DALY) have a higher effect for the global warming HH (human health) indicator than those of alpine zones (weighted value of 1.78×10^{-9} DALY). This is because of the higher rate of methane biogenic emissions from non-alpine plants (2.51×10^{-9}) than from alpine regions (1.23×10^{-10} DALY). However, the di-nitrogen mono-oxide release is greater from hydropower plants in alpine regions (5.93×10^{-12} DALY) than for non-alpine regions (3.05×10^{-15} DALY). Terrestrial ecosystem and freshwater ecosystem impacts from global warming are also higher for hydropower plants in non-alpine areas (7.56×10^{-12} species.yr) than in alpine areas (2.07×10^{-16} species.yr) due to the methane biogenic emission rates.

The ozone-formation-based impacts under the human health and terrestrial ecosystems categories are depicted in Fig. 9 for both of the considered plant locations. Both of the plants showed the same effects for ozone formation, with a weighted value of 4.87×10^{-12} species.yr for human health and 7.01×10^{-13} species.yr for terrestrial ecosystems.

The marine, freshwater and terrestrial eco-toxicity-related impacts are highlighted in Fig. 10, which is also obtained by the ReCiPe 2016 method. For all three eco-toxicity-based impact categories, both systems revealed identical effects, with a weighted value of 5.14×10^{-16} species.yr for marine, 1.46×10^{-15} species.yr for freshwater, and 5.59×10^{-14} species.yr for terrestrial.

Fig. 11 shows the water-consumption-related impacts of the plants, obtained using the ReCiPe 2016 approach. The water-consumption-based impacts mostly affect human health (weighted rate of 5.09×10^{-7} species.yr) rather than ecosystems (aquatic and terrestrial). Under this category, hydropower plants of alpine regions offered superior environmental profiles to non-alpine ones for all three impact indicators. The outcome suggests that the water consumption (human health) is

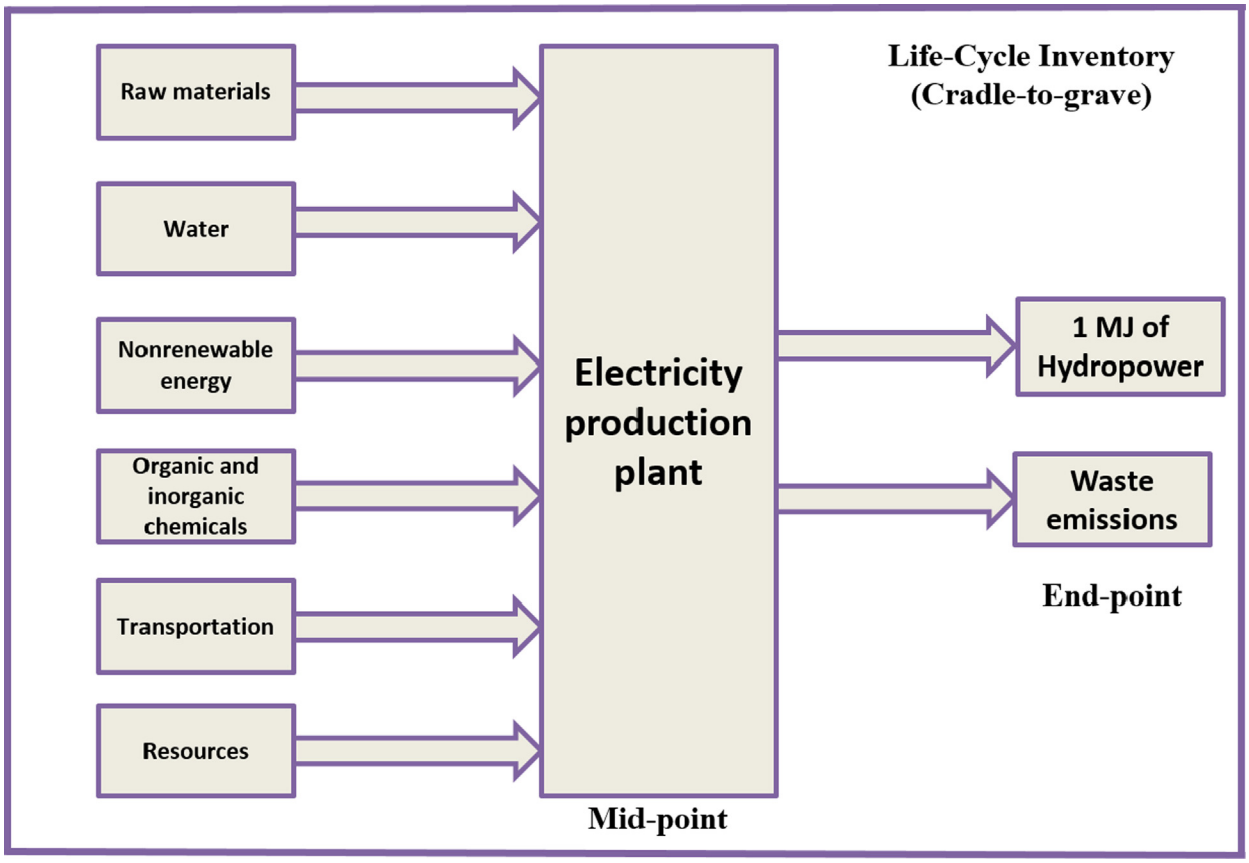

Fig. 6. LCA system boundary used in this research.

Table 4
Life-cycle inventory for LCA of the considered hydropower plants located in alpine region.

Electricity, hydropower, at reservoir power plant, alpine region/RER U/AusSD U	1	MJ
Inputs from nature	Amount	Unit
Transformation, from unknown	2.3×10^{-5}	m^2
Transformation, to water bodies, artificial	2.28×10^{-5}	m^2
Transformation, to industrial area, built up	2.3×10^{-7}	m^2
Occupation, water bodies, artificial	3.5×10^{-3}	m^2
Volume occupied, reservoir	0.15	m^3
Water, turbine use, unspecified natural origin	0.81	m^3
Energy, potential (in hydropower reservoir), converted	3.79	MJ
Inputs from technosphere		
Lubricating oil, at plant/RER U/AusSD U	7×10^{-6}	kg
Emissions to air		
Dinitrogen monoxide	7.7×10^{-8}	kg
Methane, biogenic	1.4×10^{-5}	kg
Outputs to technosphere		
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U/AusSD U	7×10^{-6}	kg

Table 5
Life-cycle inventory for LCA of the considered hydropower plants located in non-alpine region.

Electricity, hydropower, at reservoir Power plant, non-alpine region/RER U/AusSD U	1	MJ
Inputs from nature	Amount	Unit
Transformation, from unknown	2.3×10^{-4}	m^2
Transformation, to water bodies, artificial	2.28×10^{-4}	m^2
Transformation, to industrial area, built up	2.3×10^{-6}	m^2
Occupation, water bodies, artificial	3.5×10^{-2}	m^2
Volume occupied, reservoir	0.15	m^3
Water, turbine use, unspecified natural origin	8.1	m^3
Energy, potential (in hydropower reservoir), converted	3.79	MJ
Inputs from technosphere		
Lubricating oil, at plant/RER U/AusSD U	7×10^{-6}	kg
Emissions to air		
Methane, biogenic	2.86×10^{-4}	kg
Outputs to technosphere		
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U/AusSD U	7×10^{-6}	kg

higher for non-alpine regions' hydropower plants due to the water consumed for turbine use, that is 2.25 m^3, whereas it is 0.225 m^3 for hydropower plants in alpine regions.

The effects of other impact categories using the ReCiPe 2016 method, like land use, human carcinogenic and non-carcinogenic toxicity, fine particulate matter formation, ionizing radiation, stratospheric ozone depletion, freshwater eutrophication and terrestrial acidification, are depicted in Fig. 12. The impacts are almost identical for plants in both locations. The highest impact category is the fine-particulate-matter formation (weighted rate of 1.26×10^{-9} DALY) and the second-greatest effect is in the human carcinogenic toxicity

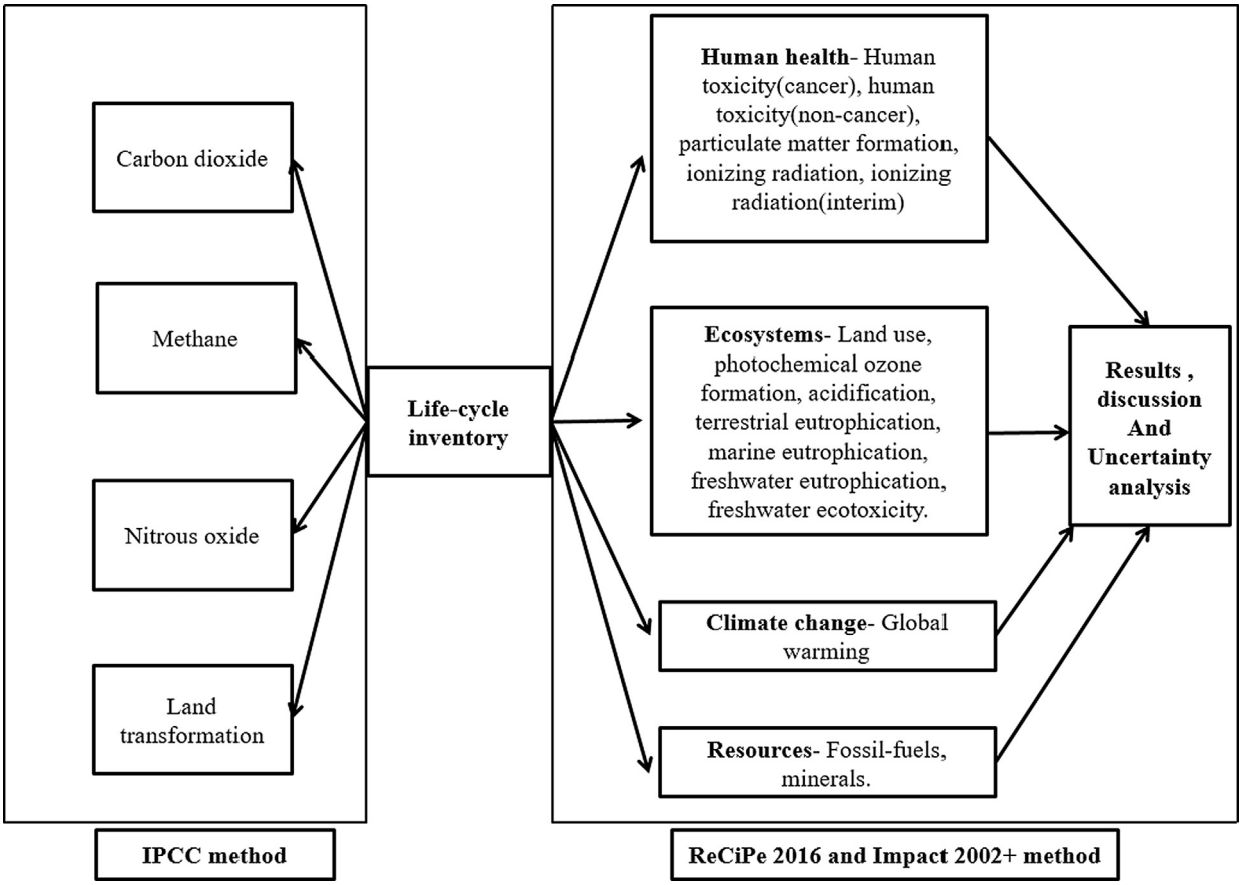
Carbon dioxide
Methane
Nitrous oxide
Land transformation
Life-cycle inventory
IPCC method
Human health- Human toxicity(cancer), human toxicity(non-cancer), particulate matter formation, ionizing radiation, ionizing radiation(interim)
Ecosystems- Land use, photochemical ozone formation, acidification, terrestrial eutrophication, marine eutrophication, freshwater eutrophication, freshwater ecotoxicity.
Climate change- Global warming
Resources- Fossil-fuels, minerals.
Results , discussion And Uncertainty analysis
ReCiPe 2016 and Impact 2002+ method

Fig. 7. LCA methods used in this research.

indicator (weighted rate of 5.28×10^{-10} DALY). The findings show that the fine particulate matter formation resulted from sulphur dioxide emission, which is 2.22×10^{-9} DALY for both of the plants.

4.1.2. End-point impact assessment outcome

The end-point environmental impacts of the considered plants are assessed by the Impact 2002+ method and the outcomes are obtained for 13 different impact indicators: carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion,

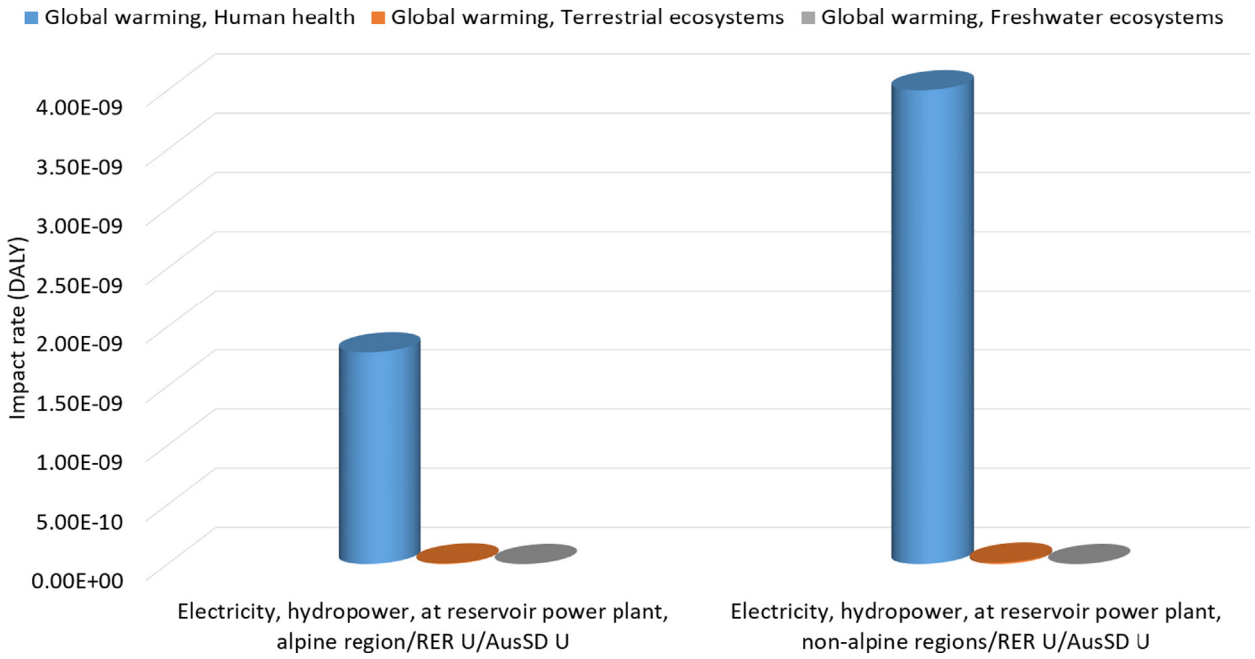

Fig. 8. Global-warming-based impacts outcome comparison.

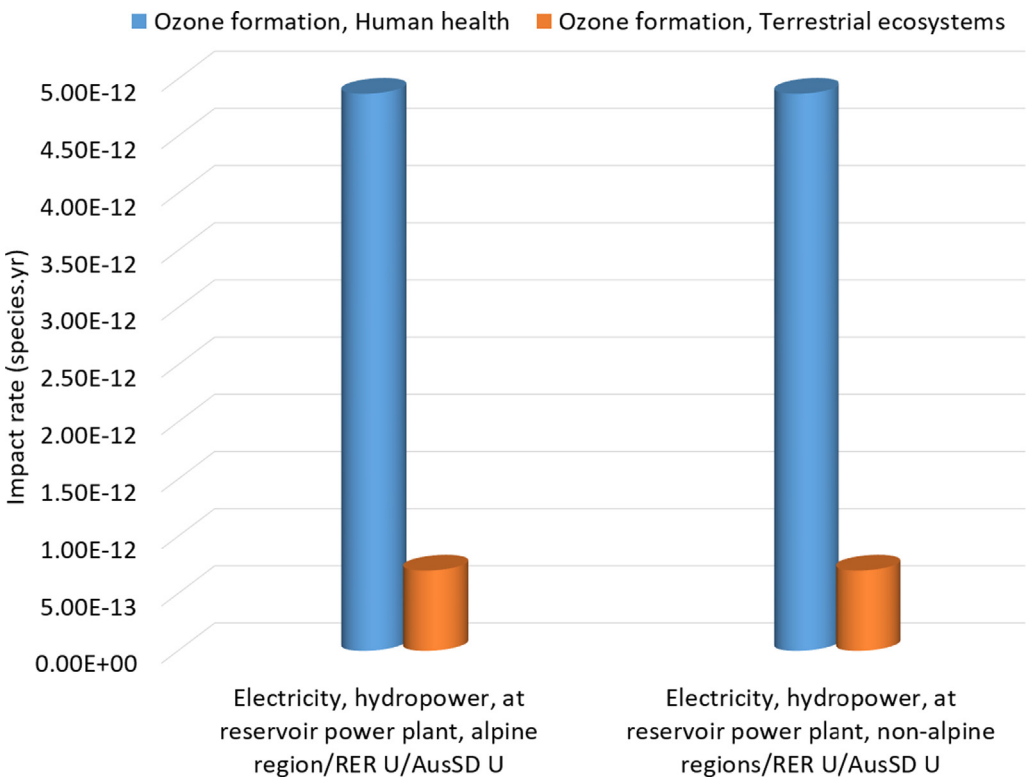

Fig. 9. Ozone formation-based impacts outcomes comparison.

respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid, land occupation, aquatic acidification, aquatic eutrophication, and global warming are estimated by this method. All the indicators provided the same amount of effects except for global warming. Hydropower plants of alpine regions are responsible for less global warming (8%) than the non-alpines (100%).

All of the 13 categories assessed by the Impact 2002+ approach are categorized into four major types of effects: resources, climate change, ecosystem quality and human health. Fig. 13 reveals that the plants of non-alpine areas (100%) are more responsible for climate change than the plants of alpine areas (8%), whilst the impacts for other three major indicators were identical for both of the plants. This is because of the rate of methane biogenic and CO_2 emissions into the air which are 3.85×10^{-4} kg CO_2-eq. and 6.26×10^{-6} kg CO_2-eq., respectively, for the hydropower plants of the non-alpine regions. However, from the hydropower plants of the alpine areas, the methane biogenic emission is

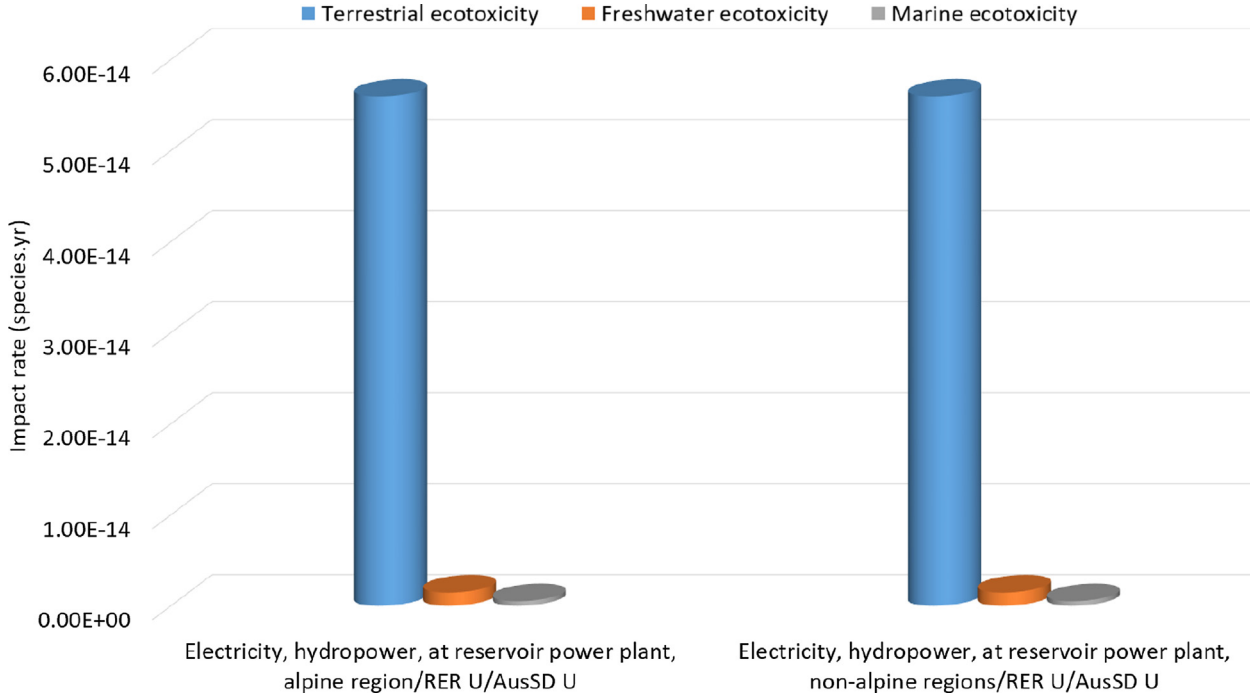

Fig. 10. Eco-toxicity-based impacts outcomes comparison.

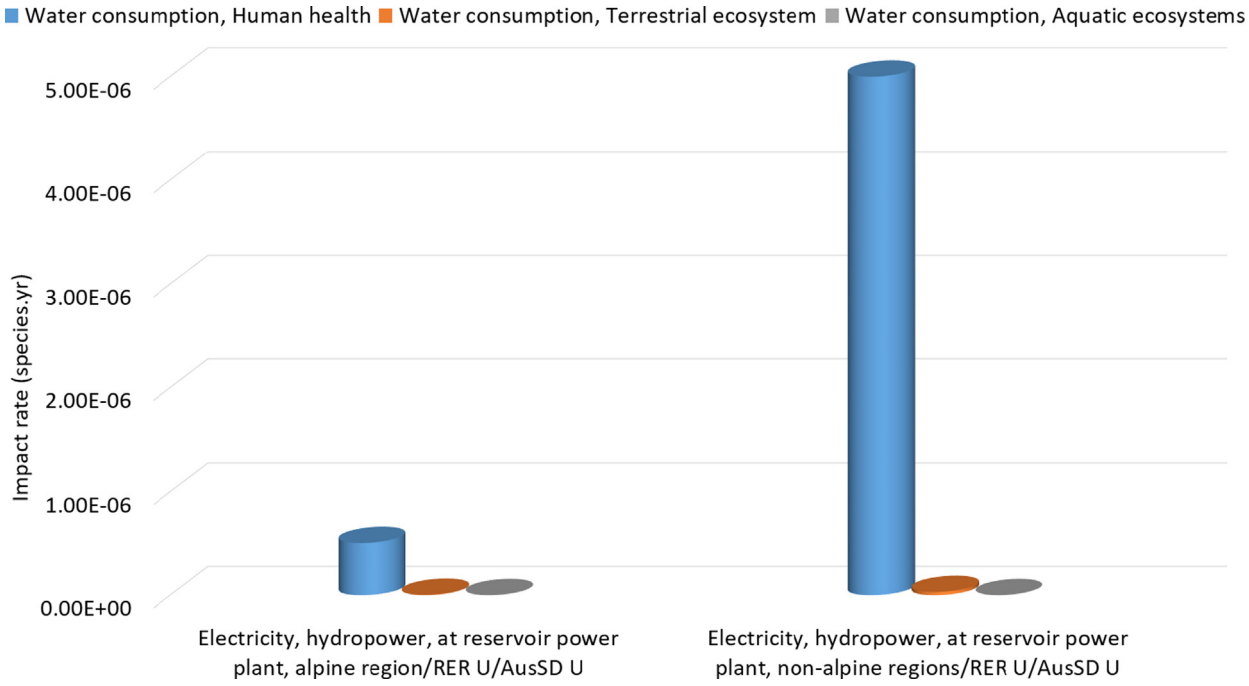

Fig. 11. Water consumption-based impacts outcomes comparison.

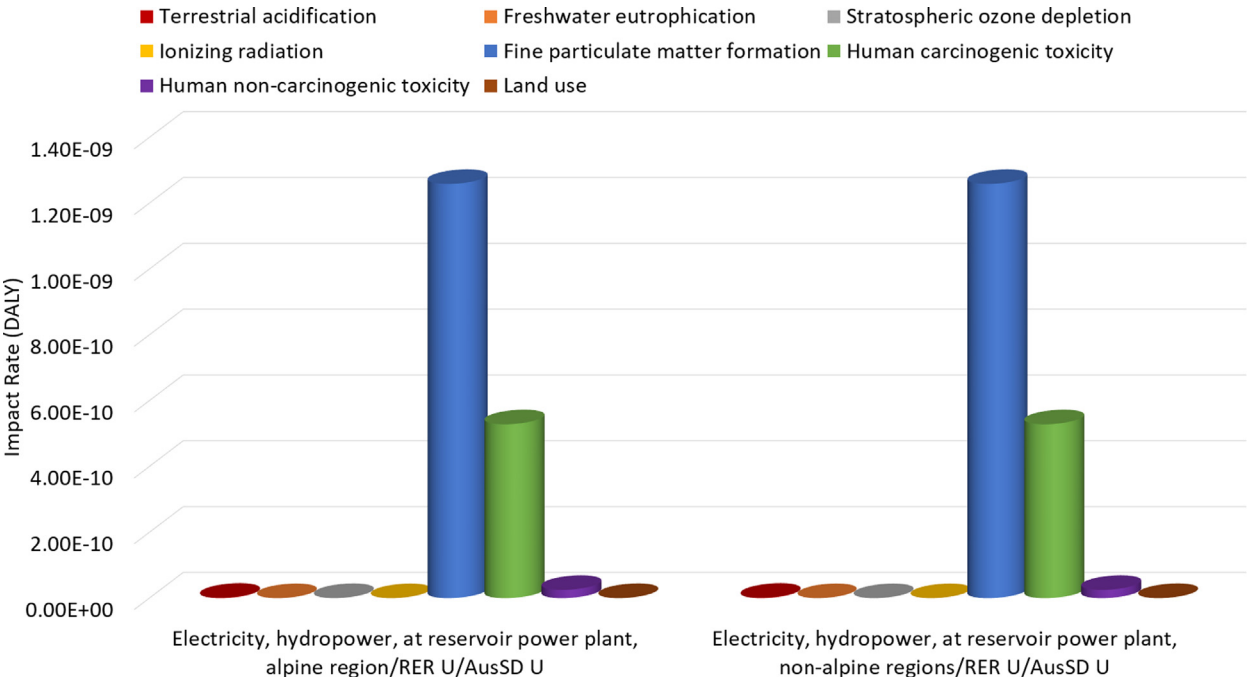

Fig. 12. Effect outcomes comparison for other impact indicators.

1.89×10^{-5} kg CO_2-eq. and CO_2 release is 6.28×10^{-6} kg CO_2-eq. For the resources, ecosystem quality and human health impact categories, the major inventory outputs are from the coal mining (8.15×10^{-12} MJ), nitrogen oxide (2.27×10^{-13} DALY) and sulphur dioxide (4.19×10^{-13} DALY), respectively.

4.2. Metal- and gas-based emission evaluation

The metal- and gas-based emissions are evaluated using the Ecopoints 97 (CH) V2.07 method for both of the considered locations of hydropower plants. The Ecopoints 97 method is a systematic way for evaluating the metal and hazardous-gas releases by any product [75]. This method assesses thirty different indicators such as carbon dioxide (CO_2), nitrous oxide (NO_x), sulphur oxide (SO_x), ammonia (NH_3), nitrogen (N), copper (Cu), cadmium (Cd), nickel (Ni), mercury (Hg), zinc (Zn), lead (Pb), phosphorous (P), and chromium (Cr). The highest rate is set to 100%. Overall, the outcomes obtained by the Ecopoints 97 method show that the lowest amount of carbon dioxide gas (1.66×10^{-2} weighted points) is emitted from hydropower plants of alpine areas as compared to non-alpine ones (2.82×10^{-1} weighted points), whereas for other indicators the impacts are the same. A smaller amount of CO_2 is released at hydropower plants of alpine zones because of maintaining the standards in manufacturing the plant provided by The Swiss Federal Institute of Aquatic Science and Technology (EAWAG, the German

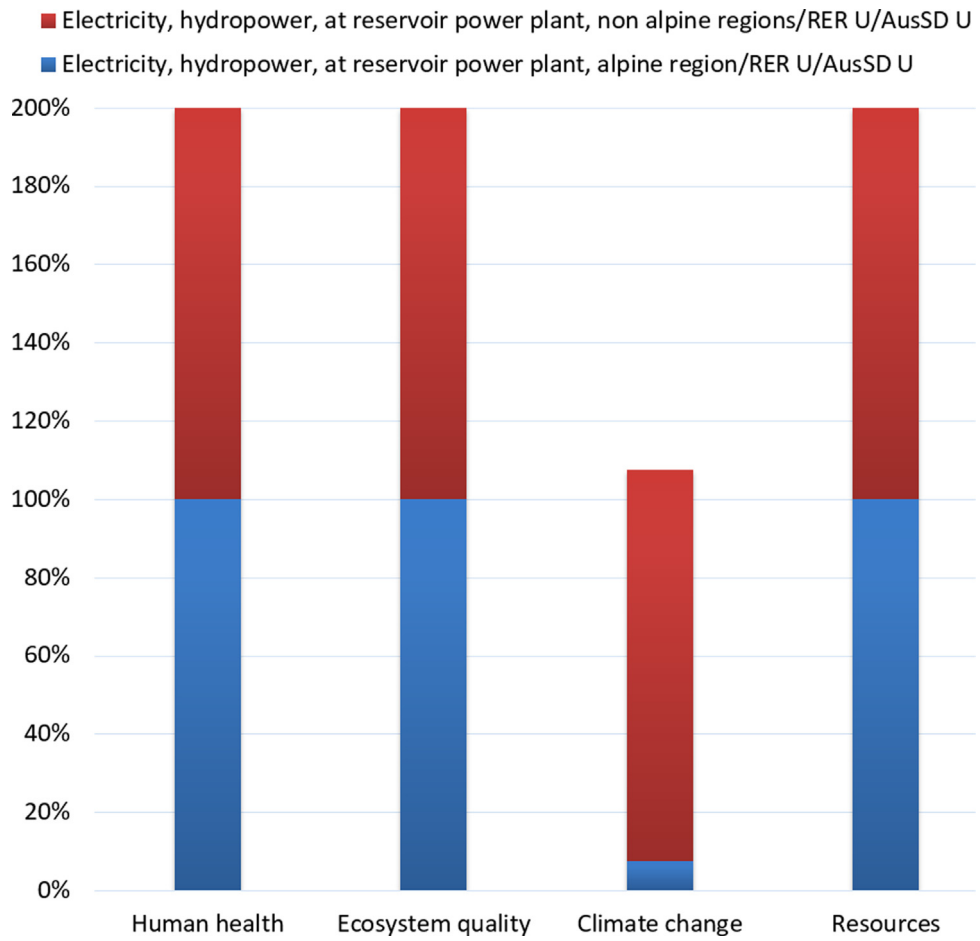

Fig. 13. Endpoint damage assessment comparison of the plants using the Impact 2002+ approach.

acronym for Eidgenossische Anstalt fur Wasserversorgung, Abwasserreinigung und Gewasserschutz) [76] and the regular removal of sediments through flushing [18].

4.3. Greenhouse-gas emission estimation

The comparison of GHG releases by the selected hydropower plants is depicted in Fig. 14, which is obtained using the IPCC approach [71]. The GHG emissions are estimatedfor a 100-year time period. The hydropower plants of alpine and non-alpine areas released identical GHG emissions for the categories carbon dioxide and land transformation. A greater amount of methane (actual value of 1.7×10^{-3} kg CO_2-eq./MJ) is emitted by the non-alpine zone's plant than by the alpine zone's (8.18×10^{-5} kg CO_2-eq./MJ) due to the long transportation of raw materials and manufactured parts to build the overall system, whereas a higher rate of nitrous oxide (6.64×10^{-6} kg CO_2-eq./MJ) is emitted to the environment by an alpine area's plant than by a non-alpine plant (7.7×10^{-9} kg CO_2-eq./MJ) due to more combustion of fossil fuels during the manufacturing of parts and more combustion of solid waste at the end-of-life waste management [77]. These research findings will guide governments and energy investors of Europe to take a well-informed decision in installing hydropower plants in alpine regions.

4.4. Comparative life-cycle inputs and outputs of the plants

The overall input–output comparison is obtained by the Raw Material Flow (RMF) method. Fig. 15 shows the inputs from nature, and the outputs to air, water, soil and solid waste using the RMF approach. All inputs and outputs are identical except for the outputs to air; alpine region-based plants released smaller emissions to the air than non-alpine-based plants. The releases to the air are higher for hydropower plants in non-alpine regions due to greater emissions of methane biogenic, 7.94×10^{-5} kg for non-alpine and 3.89×10^{-6} for alpine ones. But for di-nitrogen, mono-oxide hydropower plants of the alpine regions have greater releases (2.14×10^{-8} kg for alpine, 1.1×10^{-11} kg for non-alpine). The weighted normalized values of the total inputs and outputs of the plants of the alpine regions are about 3.98×10^{-6} and 1.19×10^{-5}, respectively. However, the overall inputs and outputs of the plants of the non-alpine zones are approximately 3.98×10^{-6} and 8.75×10^{-5}, using weighted normalization.

4.5. Energy consumption comparison

The fossil-fuel-based energy consumptions of the alpine and non-alpine hydropower plants are estimated using the CED approach [72]. The obtained outcomes are shown in Table 6. Among various kinds of energy, maximum consumption occurred from renewable sources with a normalized rate of 3.79 and 1.05 for alpine and non-alpine areas, respectively. This is because water is the main source of power used during operation of the plant. The use of nuclear and biomass power is very small for both types of plants. The hydropower plants of the alpine regions consume five times as much as the non-alpine hydropower plants. However, the coal-based energy usage by the hydropower plants of the alpine zone is about one-third that of non-alpine ones. Overall, the outcome indicates that carbon-based power consumption over the lifetime of the considered plants creates a negative impact on the environment. Therefore, future research should be carried out to reduce the use of fossil-fuel-based energy by replacing it with renewable

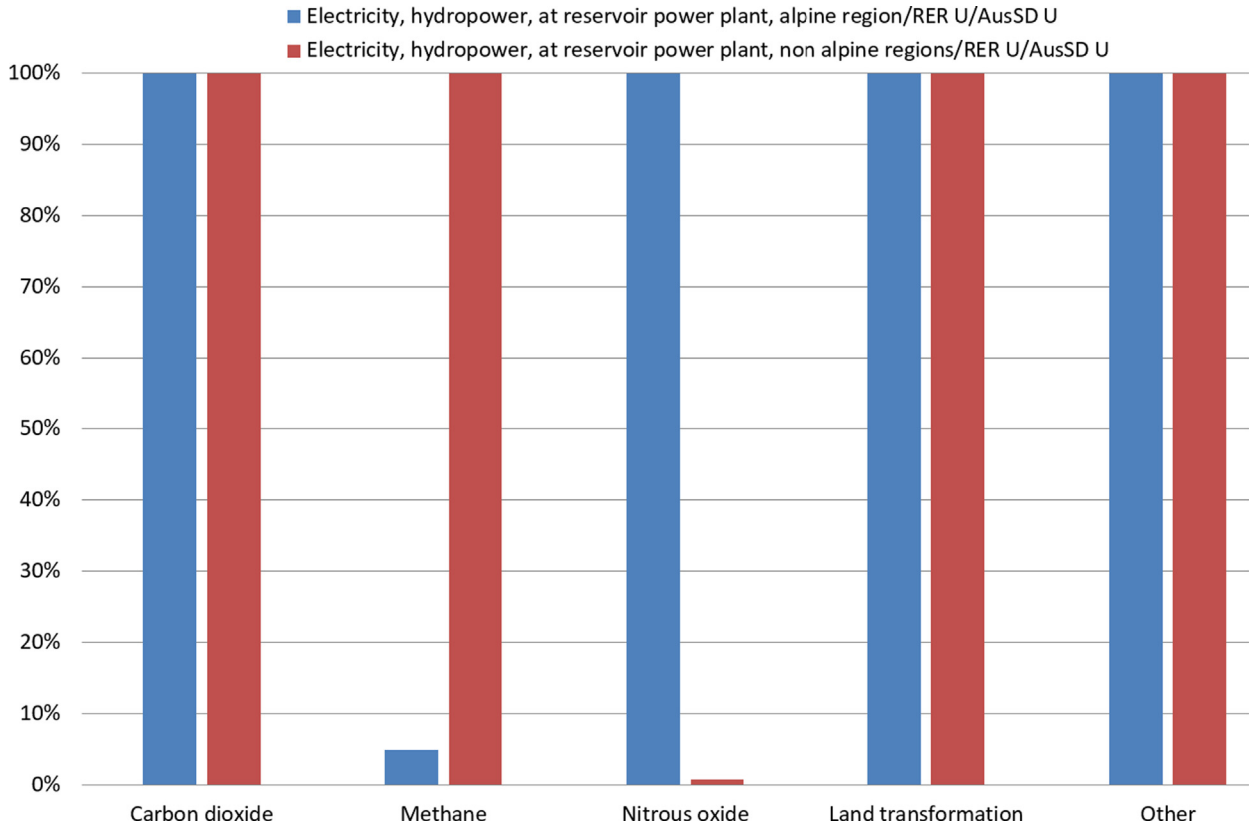

Fig. 14. Comparison of the greenhouse gas emissions by the plants, following the IPCC approach.

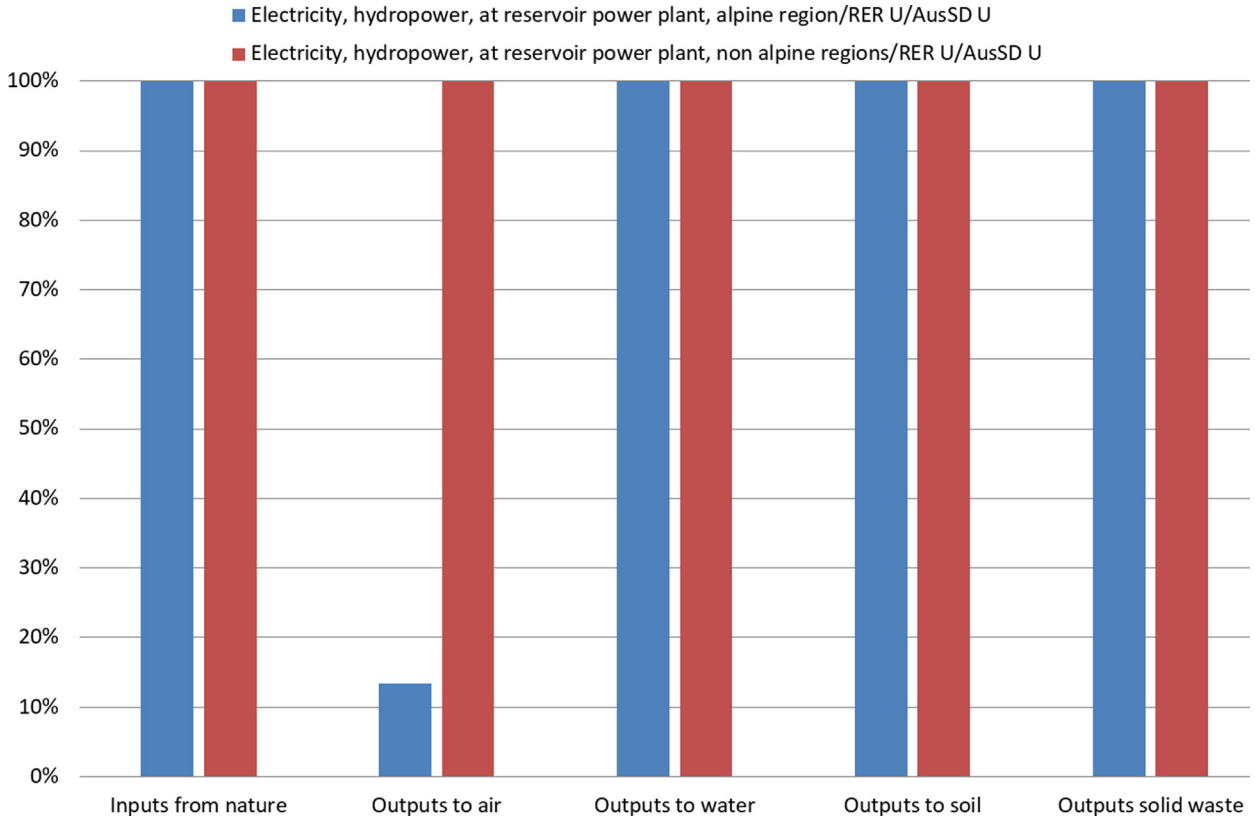

Fig. 15. Comparative life-cycle inputs and outputs of the hydropower plants of alpine and non-alpine regions by the Raw material flows method.

Table 6
Life-cycle energy consumption scenario by the considered hydropower plants, obtained by CED method.

Label	Electricity, hydropower, at reservoir power plant, alpine region/RER U/ AusSD U [MJ]	Electricity, hydropower, at reservoir power plant, non-alpine regions/RER U/ AusSD U [MJ]
Renewables	3.79	1.05
Fossil fuels - oil	5×10^{-4}	1×10^{-4}
Fossil fuels - gas	3.78×10^{-5}	1.05E-5
Fossil fuels - coal	3.03×10^{-5}	8.43×10^{-6}
Biomass	1.81×10^{-8}	5.03×10^{-9}
Nuclear	9.92×10^{-9}	2.76×10^{-9}

Table 7
Key impacts comparison with previous studies.

Country	Plant Capacity (MW)	Major Impact Category	GHG Release kg CO_2 -eq/ kWh	Dominant Material	Ref.
Europe (Alpine)	0.5–1200	GWP	1.07×10^{-4}	Construction	This study
Europe (Non-alpine)	0.5–1200	GWP	1.41×10^{-3}	Transmission line	This study
Brazil	30.3	GWP	5.46	Transport	[33]
Canada	10	GWP	15.2	Construction	[34]
China	3.2	GWP	7.6	Reservoir	[27]
India	3	GWP	74.88	Turbine	[30]
Indonesia	8	ETP	1.2	Pipeline	[31]
Japan	10	GWP	11.3	Construction	[29]
Thailand	3	GWP	52.7	Transmission line	[32]

energy.

5. Discussion

5.1. Impacts outcome comparison with previous studies

The construction phase is responsible for most impacts by the hydropower plants of alpine areas in Europe, whereas the transmission line is the case for non-alpine areas (Table 7). According to Siddiqui et al., the construction and decommissioning phases are the major contributors to environmental impacts [34]. If biomass decay is considered, it may be a significant contributor to global warming, highlighted by them. The obtained human toxicity and photochemical ozone creation values are 0.0047 g dichlorobenzene-eq./kWh and 0.000768 g ethane-eq./kWh, respectively, whereas the global warming potential value is 15.2 g CO_2-eq./kWh. Hanafi et al. showed that the highest impact is on marine aquatic eco-toxicity, freshwater eco-toxicity and abiotic depletion for a hydropower plant in Indonesia [31]. The main sources of these impacts are rapid pipelines (59%) and building construction (20.5%). The obtained greenhouse gas emission rate is 1.2 kg CO_2-eq./MWh.

However, according to Li et al. from China the greenhouse gas emission rate of a hydropower plant is 7.6 ± 1.09 g CO_2-eq./kWh [28].

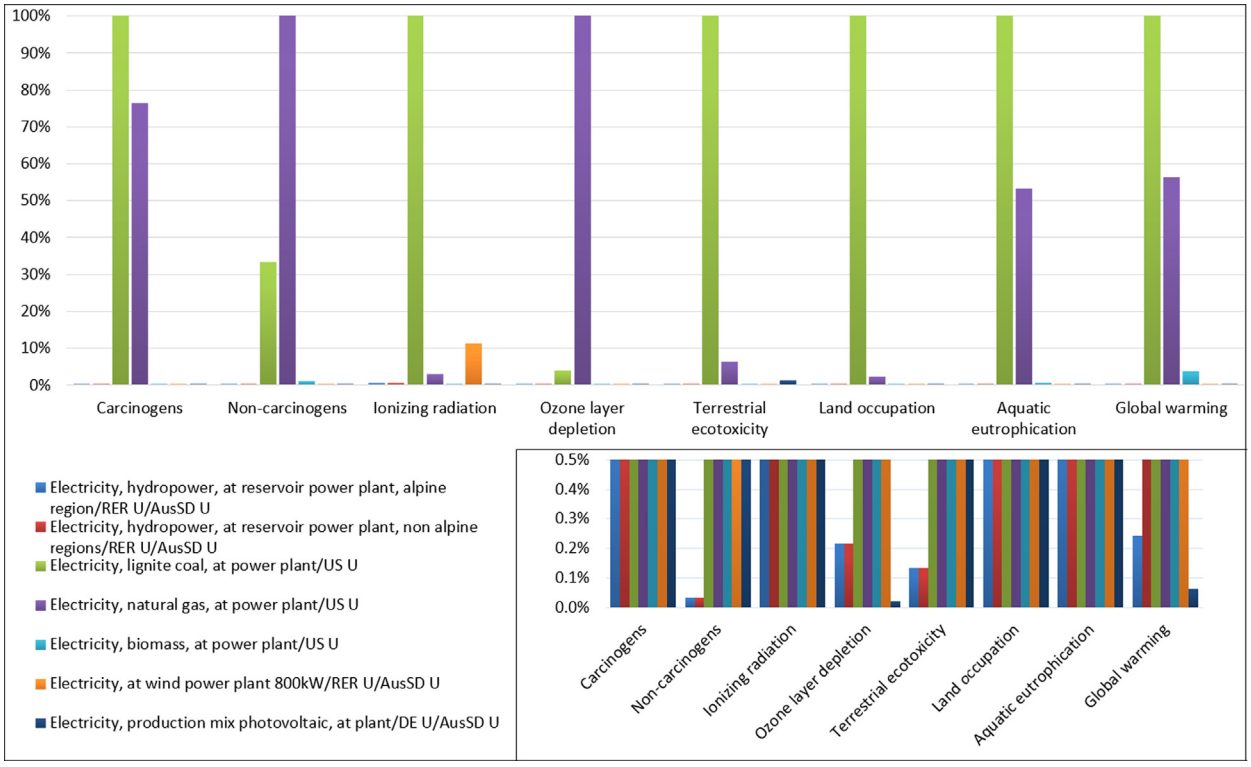

Fig. 16. Environmental impacts comparison for various power plants.

Table 8
Key impacts comparison with various plants.

Impact category	Electricity, hydropower, at reservoir power plant, alpine regions	Electricity, hydropower, at reservoir power plant, non-alpine	Electricity, lignite coal, at power plant	Electricity, natural gas, at power plant	Electricity, biomass, at power plant	Electricity, at wind power plant	Electricity, production mix photo- voltaic, at plant	Unit
Carcinogens	2.18×10^{-8}	2.18×10^{-8}	3.12×10^{-4}	2.38×10^{-4}	8.33×10^{-7}	7.35×10^{-7}	4.01×10^{-8}	kg C_2H_3Cl eq
Non- carcinogens	5.89×10^{-8}	5.89×10^{-8}	5.89×10^{-3}	1.76×10^{-2}	1.64×10^{-4}	1.37×10^{-6}	1.05×10^{-6}	kg C_2H_3Cl eq
Ionizing radiation	2.08×10^{-8}	2.08×10^{-8}	4.47×10^{-6}	1.28×10^{-7}	8.56×10^{-9}	4.98×10^{-7}	3.08×10^{-9}	Bq C-14 eq
Ozone layer depletion	1.17×10^{-12}	1.17×10^{-12}	2.12×10^{-9}	5.41×10^{-8}	7.02×10^{-11}	2.80×10^{-11}	1.20×10^{-13}	kg CFC-11 eq
Terrestrial ecotoxicity	5.37×10^{-6}	5.37×10^{-6}	4.02×10^{-1}	2.47×10^{-2}	5.01×10^{-4}	1.81×10^{-4}	4.70×10^{-3}	kg
Land occupation	3.01×10^{-8}	3.01×10^{-8}	5.62×10^{-4}	1.23×10^{-5}	1.07×10^{-6}	7.04×10^{-7}	3.91×10^{-7}	m^2
Aquatic eutrophication	9.466×10^{-10}	9.46×10^{-10}	1.28×10^{-5}	6.81×10^{-6}	6.31×10^{-8}	2.22×10^{-8}	2.29×10^{-8}	kg
Global warming	2.97×10^{-5}	3.92×10^{-4}	1.21	6.84×10^{-1}	4.45×10^{-2}	1.81×10^{-4}	7.59×10^{-6}	kg CO_2 eq

Table 9
Key damage comparison with various plants.

Damage category	Electricity, hydropower, at reservoir power plant, alpine region/RER U/AusSD U	Electricity, hydropower, at reservoir power plant, non alpine regions/RER U/AusSD U	Electricity, lignite coal, at power plant/ US U	Electricity, natural gas, at power plant/US U	Electricity, biomass, at power plant/US U	Electricity, at wind power plant 800 kW/RER U/ AusSD U	Electricity, production mix photovoltaic, at plant/DE U/ AusSD U	Unit
Human health	1.67×10^{-12}	1.67×10^{-12}	9.12×10^{-7}	4.20×10^{-7}	1.31×10^{-7}	4.11×10^{-11}	6.36×10^{-12}	DALY
Ecosystem quality	1.22×10^{-7}	1.22×10^{-7}	3.73×10^{-2}	1.48×10^{-2}	4.79×10^{-3}	3.37×10^{-6}	4.02×10^{-5}	m^2
Climate change	2.97×10^{-5}	3.92×10^{-4}	1.21	6.84×10^{-1}	4.45×10^{-2}	1.81×10^{-4}	7.59×10^{-6}	kg CO_2 eq
Resources	8.15×10^{-12}	8.15×10^{-12}	20.52	12.63	3.42×10^{-2}	1.95×10^{-10}	8.19×10^{-12}	MJ

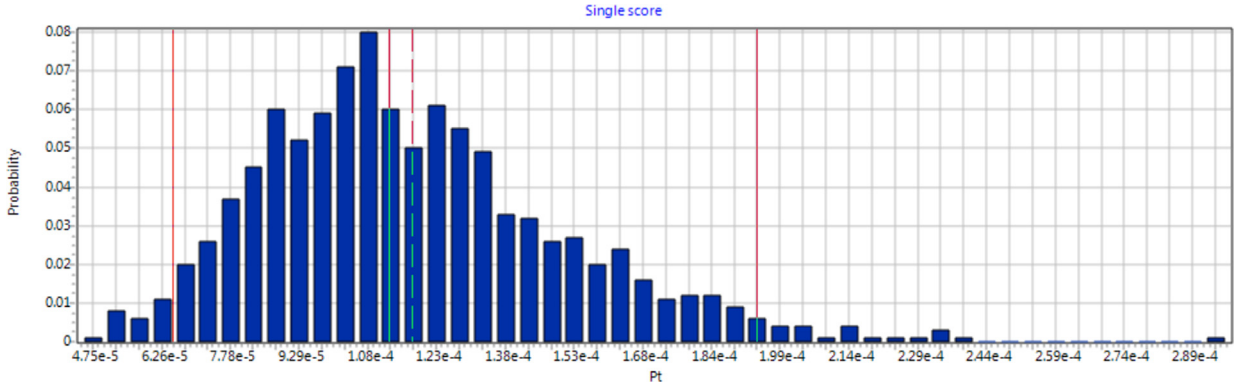

Fig. 17. Probability distribution for the single-score impact category of hydropower plants of alpine zones.

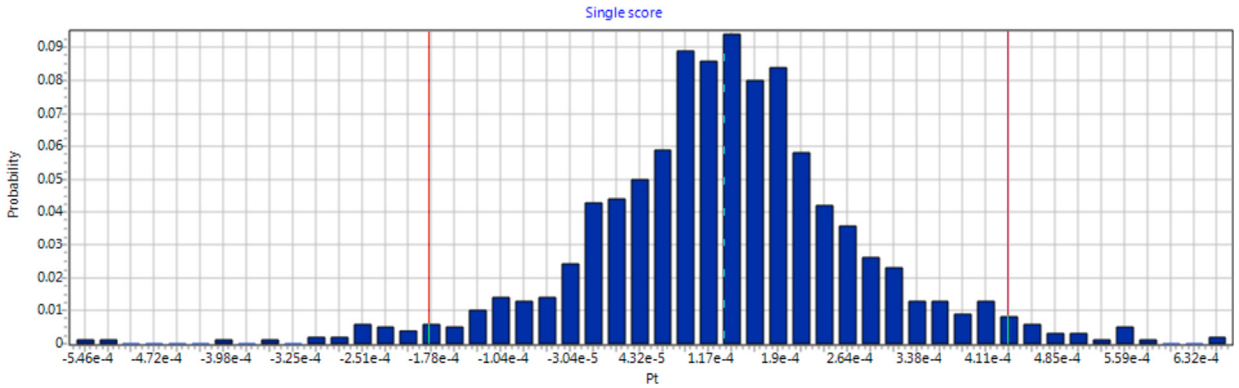

Fig. 18. Probability distribution for the single-score impact category of hydropower plants of non-alpine zones.

The reservoir and dam are the most sensitive factors for GHG emissions. The potential release of methane from sediment in the phase of dam decommission plays a crucial part in its overall impact. Thailand-based research group Pascale et al. found that the global warming potential and photochemical ozone creation rates are 52.7 g CO_2-eq./kW and 0.03 g ethane eq./kW, respectively, considering a cradle-to-grave LCA analysis of the hydropower plant [32], whereas the amount of greenhouse gas release by hydropower plants of the non-alpine areas is 1.41×10^{-3} kg CO_2-eq./kWh. The transmission line is the dominant component in almost all life cycle impact assessment categories with the exception of abiotic depletion. The distribution network and penstock also provide a large percentage of the environmental impacts. Geller et al. showed that the global warming potential, human toxicity and freshwater eco-toxicity of a hydropower plant in Brazil are 5.46 kg CO_2-eq./MW, 7.28 kg 1,4-dichlorobenzene-eq./MW, 2.45 kg 1,4-dichlorobenzene-eq./MW, respectively [33]. Transport is the most crucial emitter since most of the equipment and materials for plant construction were brought from distant locations, through various means of transportation.

The key finding from another research group in China (Pang et al.) is that the main impact of a hydropower plant occurs in the construction phase [27]. The small hydropower plants of Thailand and Japan work similarly to those of China, but worse than the plant in Switzerland. According to this research, for the considered case the global warming potential value is 28.4 kg CO_2-eq./MWh, the abiotic depletion value is 91.6 g antimony-eq./MWh, the freshwater eco-toxicity value is 11.1 kg dichlorobenzene-eq./MWh, and the photochemical ozone creation rate is 9.3 g C_2H_4-eq./MWh. About 96.1% of the global warming potential is incurred at the construction stage. Hondo et al. from Japan discovered that construction of hydropower plants is the dominant phase for the global warming potential, which constitutes 82.8% of total greenhouse gas emission. The amount of global warming potential by the considered hydropower plant in Japan is 11.3 kg CO_2-eq./kWh [29], whereas the greenhouse gas emission rate by the hydropower plant of the alpine area in Europe is found 1.07×10^{-4} kg CO_2-eq./kWh. The difference in impact outcome by the hydropower plants of different countries is due to the change in available resources, raw materials, transportation distances of plant elements, and combustion rates of fossil fuels during the manufacturing of parts and the end-of-life waste management. Overall, the construction phase is responsible for the impacts on all categories, the operation phase is responsible for abiotic depletion and freshwater eco-toxicity, and transportation is accountable for acidification, for a typical hydropower plant.

5.2. Impacts comparison with other power plants

According to the endpoint indicator based results analysed by the Impact 2002+ method, electricity generated by hydropower plants in both alpine and non-alpine regions show greater environmental sustainability over electricity generated by other sources like lignite coal, natural gas, biomass, wind, and photovoltaic. From the eight major impact categories, electricity generated by lignite coal has the most detrimental effect overall for all impact categories except non-carcinogens and ozone layer depletion (Fig. 16 and Table 8), whereas for the non-carcinogens and ozone-layer depletion categories, electricity generated by natural gas has the most adverse effect. Electricity generated by wind produces more ionizing radiation than other sources. Electricity generated from biomass has lower impacts like hydropower for most of the impact indicators. In a comparison between electricity generated by alpine and non-alpine hydropower resources, they have a very similar impact on the environment throughout all the categories except global warming. Non-alpine hydropower plants affect more in terms of global warming. A similar scenario is observed in Table 9, which shows a comparison of power plants based on damage categories. Coal-based power plants affect human health, ecosystem quality,

climate change, and resources more than other power plants. Overall, hydropower plants in alpine regions are better in terms of climate change than other plants.

5.3. Uncertainty analysis

The uncertainty distributions of the two estimations for the considered hydropower plants are shown in Figs. 17 and 18, found by the Eco-Indicator 99 method. The bars with maximum height show the greatest probabilities. The estimated life-cycle single-score points of alpine and non-alpine region-based hydropower plants were $1.18E^{-4} \pm 3.34E^{-5}$ (mean ± standard deviation) and $1.33E^{-4} \pm 1.43E^{-4}$, respectively. The smaller standard deviation in the single-score points of alpine-zone hydropower plants indicates lower impact probabilities than for non-alpine zones. Overall,the small bars for about 70% of the total numbers depict that hydropower plants of both regions are environmentally superior to other plants.

6. Limitations and future improvements

The main limitations and future improvements of this research are outlined as follows:

- Pumped storage plants are not separated during the estimation of reservoir plants average rates at the used data source.
- Environmental impacts caused by individual components of the hydropower plants have not been assessed separately in this work.
- The environmentally impactfull elements can be replaced by sustainable alternatives, which is required to be assessed by further sensitivity analysis.
- Life cycle cost analysis or techno-economic analysis have not been conducted in this study due to the lack of sufficient data, which can be of great attention in future.

The future direction of this research work would be to solve the above-mentioned issues for greener hydropower production in the near future.

7. Conclusion

In conclusion, a comparative assessment of the environmental impacts of an alpine and a non-alpine region-based hydropower plant is highlighted. To confirm the efficacy of this LCA analysis, (i) a new comprehensive LCI for both types of plants is developed, (ii) impacts are assessed by several methods, and (iii) an uncertainty analysis of both frameworks is carried out to judge their effectiveness. This research work is unique as it quantifies the ecological effects by several systematic methods for the first time and considers both the midpoint and the endpoint approaches in assessing the effects from both installations, utilizing the Impact 2002+ approach. The novel findings of this research are that hydropower plants in alpine regions are environment-friendly and have only 8% carbon dioxide emission with a smaller climate change effect. On the other hand, hydropower plants in non-alpine regions have high carbon dioxide emissions with a greater climate change effect. The obtained outcome from the IPCC, ReciPe 2016, Impact 2002+ methods is that the global warming effects from hydropower plants in non-alpine regions (3.92×10^{-4} kg CO_2-eq./MJ) are higher than for plants in alpine regions (2.97×10^{-5} kg CO_2-eq./MJ). Moreover, the GHG emission estimation shows that alpine-region based plants offer one-tenth the methane release of non-alpine-region based plants. However, both alpine and non-alpine region-based hydropower plants are more environment-friendly electricity generation sources than lignite coal, natural gas, biomass, wind, or photovoltaic. Overall, it can be concluded that, to augment clean hydropower generation, future research should be focused on finding the most hazardous materials in plant installation and replacing them with analogous ecologically superior alternatives.

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